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Variability of Indian monsoon and its rainfall forecasting

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Abstract : The present state of knowledge on the variability of Indian monsoon with special emphasis on the intra-seasonal and inter-annual variation of the monsoon giving importance to 'monsoon jets', seasonal oscillations, annual variability and coherent intra-seasonal oscillations are discussed at length. Different techniques and models implemented for forecasting monsoon rainfall have been thoroughly considered. A link between stratosphere and monsoon rainfall is examined. The instability characteristics of monsoon disturbances are outlined. Finally, scope of future investigations are pointed out.

Keywords : Monsoon, rainfall, instability characteristics

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1. Introduction

Monsoon is defined as a seasonal shift in wind direction. In a true monsoon climate, seasonal wind shifts typically cause a drastic change in the general precipitation and temperature patterns. However, the monsoon may be associated with dry weather as well, since the 'wet' monsoon phase of warm, moist air is seasonally replaced by a 'dry' monsoon of cool, dry air. This phenomenon is the dominant feature of low-latitude climates stretching from West Africa to the western Pacific Ocean. To understand why these are more favored areas, we need knowledge of the driving forces behind monsoons and the Earth's weather in general [1,2].

The annual monsoon cycle can be described as a result of the annual variation of incoming solar radiation and the differential heating at the surface of land and water. This has been recognized for hundreds of years, as Webster [3] noted in his discussion of monsoon dynamics. Simply stated, sections of the earth's surface heat and cool at different rates depend on their ability to absorb solar radiation and the time of year. Bodies of water, which can absorb sunlight at varying depths (and consequently reflect less back to the atmosphere), store energy more efficiently than land and therefore retain heat longer than a land mass. Due to the shallowness of the absorbing surfaces, the land surfaces gain or lose heat at a quicker rate. To maintain an energy balance, heat is transferred from areas of surplus to deficit, and in the case of a land-water differential, this is accomplished through a phenomenon known as the "land-sea breeze". As the hot air rises over the land, it is replaced by the cooler air over the water. At night, however, the land cools at a quicker rate than the water, so the wind shifts, blowing from the land to the warmer water.

To ensure sustainable agriculture in a region, knowledge of the local climate is essential [4,5]. Climatic limitations are a strong indicator of agronomic potential and can be used to determine which crops are best suited for a region, as rainfall and temperatures are two major variables affecting crop type and yield. So agricultural planning is especially critical in monsoon regions, which experience distinct wet and dry seasons.

This paper reviews the variability of Indian monsoon with special emphasis on the intra-seasonal and inter-annual variation of the monsoon giving importance on 'monsoon jets', seasonal oscillations, annual variability and coherent intraseasonal oscillations. Different techniques and models implemented for forecasting monsoon rainfall have been thoroughly considered. A link between stratosphere and monsoon rainfall is examined. The instability characteristics of monsoon disturbances are outlined and scopes of future investigations are pointed out.

2. Intra-seasonal and inter-annual variations

The seasonal mean and its inter-annual variability are influenced by the intra-seasonal oscillations (ISO's) [6] of the Indian summer monsoon, as the intra-seasonal and inter-annual variations are influenced by a common mode of spatial variability. The frequency of chaotic ISO regimes determines the seasonal mean monsoon and thus sets a limit on monsoon predictability. A higher frequency of active (break) conditions within a monsoon season causes a strong (weak) summer monsoon.

The predictability of the Indian summer monsoon is determined on whether the inter-annual summer monsoon variability is dominated by the slowly varying external forcing or by internal processes. If the intra-seasonal anomalies related to the 'active' ('break') condition enhance (weaken) the large-scale monsoon flow, a larger frequency of 'active' ('break') conditions could result in a stronger (weaker) than normal seasonal mean monsoon. The ISO's are characterized by a broadband spectrum with period between 10 and 90 days and are not pure sinusoidal oscillations. Thus the duration of 'active' and 'break' conditions during a monsoon season could be different. The number of 'active' and 'break' episodes in a monsoon season could also be unequal due to their initial phases, as these are low frequency oscillations.

The ISO's and inter-annual variability of the Indian summer monsoon are governed by a common mode of spatial variability. Ferranti *et al* [7] reported that the intra-seasonal and inter-annual variability simulated by a general circulation model (GCM) are almost similar. Goswami *et al* [8] used daily observations of surface wind for a period of 10 years and found that the spatial structures of the intra-seasonal and inter-annual variability are similar. In Figure 1, the geographical distribution of the intra-seasonal activity and the inter-annual variability [9] are compared. Annamalai *et al* [10] used NCEP/NCAR re-analysis for 17 years (1979-1995) but could not find a common mode of variability, which describes intra-seasonal and inter-annual variability of the monsoon. Palmer [11] introduced the concept of 'nudged chaos' where the ISOs could be intrinsically 'chaotic', but the slowly varying forcing could 'nudge' them to reside in either one of the two possible equilibria for a long enough time and thereby influence the seasonal mean. Annamalai *et al* [10] examined the statistics of the ISO's that are modulated by the slowly varying boundary forcing (El Ninos and La Ninas). But due to the small sample size (number of El Ninos and La Ninas within that period), the statistical significance of their results were not very certain. Ajaya *et al* [5] used daily data of 42 years and proposed a method to separate the contribution of the ISO's, to the seasonal mean, from that of the external forcing. They found that the intra-seasonal and inter-annual monsoon

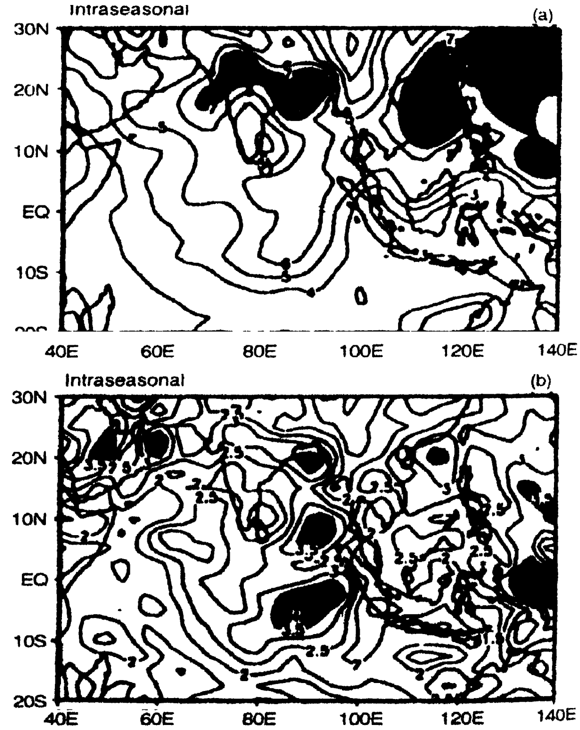

Figure 1. Geographical distribution of intra-seasonal and inter-annual activity.

(a) Mean std dev of ISO-filtered relative vorticity (10^{-6} s^{-1}) at 850 hPa from 1 June to 30 September for 20 years (1978-97)

(b) Inter-annual std div of seasonal mean relative vorticity (JJAS 10^{-6} s^{-1}) based on the same 20 years.

variability is indeed governed by a common mode of spatial variability and that the ISO's make dominating contribution to the inter-annual variability.

For a given year, the 'active' ('break') days are those for which wind anomalies are greater (lesser) than the +1 SD (-1 SD). It has found that a small shift of the reference point does not significantly affect the definition of 'active' and 'break' days. In fact, the composite of daily precipitation during 'active' days closely corresponds to the canonical pattern of daily rainfall variability associated with typical 'active' and 'break' condition of the Indian monsoon. A typical 'active' condition is associated with strengthening (weakening) of the seasonal mean low-level monsoon circulation, enhancing (weakening) the cyclonic vorticity and convective activity in the northern position of the Tropical Convergence Zone.

2.1 *Intra-seasonal 'monsoon jets'*

Most of the year, the Climatological winds over the equatorial Indian Ocean is westerly. In 1973, Wyrtki [12] reported that in April-May ('spring') and October-December ('fall'), strong, sustained westerly winds generate eastward jets in the ocean. Climatological winds in the EqIO are related to the seasonal north south migration of the Tropical Convergence Zone (TCZ). The TCZ is centered on the equator in spring and autumn, leading to strong westerlies during these periods. The semi-annual cycle, the winds in the region also have strong intra-seasonal oscillations (ISO) [13,14]. These are associated in summer with fluctuations of the Asian summer monsoon [15,17] and in winter with Madden-Julian oscillation (MJO) [18]. Although the time resolution of the TOPEX (Radar) data is not sufficient to capture the effects of high frequency intra-seasonal jets, the agreement between model dynamic height and TOPEX sea surface height suggests that the model simulation of zonal currents is reliable [19] This is shown in Figure 2.

The monsoon jets have been recently observed using an acoustic current meter mounted on a mooring at 90^{0}E on the equator [20]. The westerly bursts in summer (June-September) are associated with ISO of the summer monsoon, and in January-March with MJO. To understand the origin of the monsoon jets we have to study the relationship between convection, wind stress and currents in the EqIO and then examine the role of equatorial upper ocean dynamics in the selective response to westerly bursts. Summer monsoon ISO's is characterized by a bimodal meridional structure of atmospheric convection [14,17,18]. In the 'active phase' of the monsoon, there is organized deep convection over the North Bay of Bengal and the Gangetic plains. During a 'monsoon break', convection in this region is suppressed, while there is deep convection over the central and eastern EqIO (Equatorial Indian Ocean). The monsoon jet decelerates a few days after the wind stress begins to fall because the westward ZPG (Zonal Pressure Gradient), enhanced by the jet itself, becomes larger than the eastward stress. The wind stress is weakly eastward or zero, the unbalanced ZPG can give rise to westward currents, as in August of 2000 and 2002. Subsequent wind bursts do not generate eastward jets. During January-March, the wind bursts in the eastern EqIO are considerably weak than in summer. The equatorial currents are therefore predominantly westward, although the bursts do give rise to eastward acceleration. The monsoon jet has the vertical structure expected from theory [21,22]; it is about 100 m deep, whereas the WJ (Westerly Jet) can extend upto a depth of 120 m in the east.

2.2 *Intra-seasonal oscillations of monsoon*

Active and break episodes, are associated with enhanced (decreased) rainfall over central and western India and decreased (enhanced) rainfall over the southeastern peninsula and eastern India [23,24]. The intra-seasonal variations of rainfall (active-break cycles) are strongly coupled to the intra-seasonal

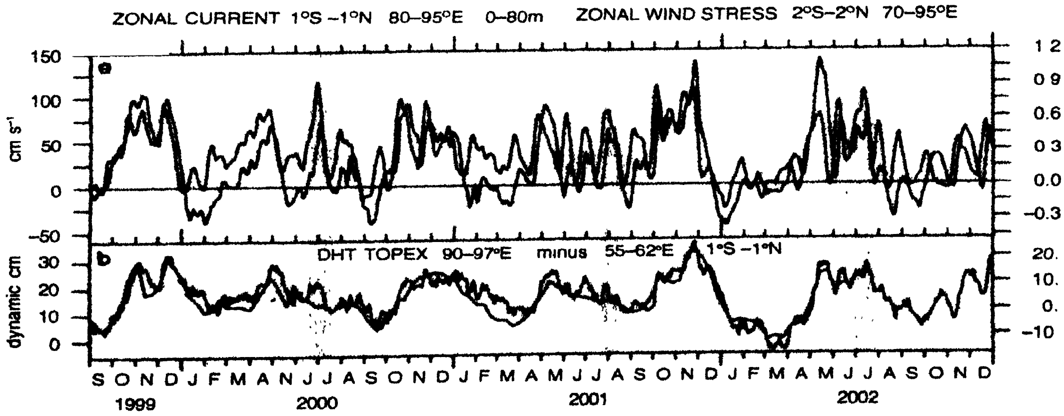

Figure 2. Time series of (a) 10-day running mean zonal wind stress (dynes cm^{-2}; thin) and model daily upper ocean zonal current (cm s^{-1}; bold). (b) 10-day TOPEX sea surface height anomaly (cm; thin) and model daily dynamic height (DHT; dynamic cm; bold) difference between eastern and western EqIO.

variations of circulation [17,25,26]. Recent studies [16,17,26] have shown that the spatial structure of monsoon ISO is such that they strengthen the seasonal mean circulation in one phase while weakening it in the opposite phase. Therefore, the monsoon ISO has the potential to modulate the frequency of occurrence of LPS (low pressure system) by alternately enhancing and weakening the zonal wind shear and low level cyclonic vorticity in the monsoon trough (MT). Daily NCEP/NCAR (National Center for Environmental Prediction / National Center for Atmospheric Research) reanalysed winds [27] at 850-hPa levels for the period 1954-1993 can be used for studying the large-scale intra-seasonal variability of circulation. Pentad Climate Prediction Center Merged Analysis of Precipitation (CMAP) for the period 1979-2000 [28] can be used to describe the large-scale monsoon intra-seasonal oscillations in rainfall. The frequency of occurrence of the monsoon synoptic systems as a function of phase of the ISO can be determined using an index of ISO activity. The relative vorticity at 850-hPa represents monsoon activity quite well on intra-seasonal time scales [16,17,26]. Therefore, a monsoon intra-seasonal index (MISI) can be defined [29] as the 10-90 day filtered relative vorticity at 850-hPa averaged over 80^0 E - 95^0 E, 12^0 N - 22^0 N, which represents the core region of the MT. The index is constructed each year from 1 June to 30 September for 40 years and normalized by its own standard deviation. A sample of normalized MISI for 10 years is shown in Figure 3(a), 3(b). The total number of LPS during the 40-year period is 510, with a seasonal average of 12.5. The frequency distribution of genesis of LPS as a function of phase of the ISO can be obtained by putting the genesis dates of all the LPS during the 40-year period (1954-1993) into bins of MISI [29] size 0.25. This is illustrated in Figure 3(b). Out of the 510 LPS, 350 occur in the positive phase of the ISO and 160 occur in the negative phase. As lows and depressions are the main rain-bearing systems of the monsoon, the spatial and temporal clustering of LPS is essentially responsible for increasing (decreasing) rainfall over central India during active (break) conditions. We can understand how the ISO achieves this clustering, by examining the modulation of the low level circulation at 850 hPa by the ISO. It is noted that the vorticity in the monsoon trough may increase (decrease) by 50% during an active (break) spell. The enhancement of shear and low level cyclonic vorticity in this region in the positive phase of the ISO increases the probability of genesis of LPS. A similar mechanism is responsible for clustering of tropical cyclones and hurricanes in Gulf of Mexico [30], eastern Pacific [31] and western Pacific, through modulation of circulation by the MJO.

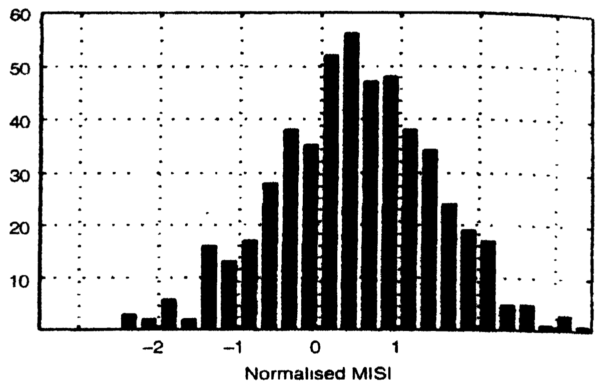

Figure 3. (b) Histogram of genesis of LPS (low and depressions) for the Indian monsoon region (50^0 E - 100^0 E, Eq- 30^0 N) during June to September for the period of 1954-1993 as a function of normalized MISI

The 10-80 day filtered OLR (Outgoing Long wave Radiation) anomalies averaged over $85\text{-}90^0$ E, $15\text{-}20^0$ N shows the large variability of convection associated with monsoon ISO over the North Bay of Bengal (BOB). Sea surface temperature has highest intra-seasonal variability in BOB and the northern South China Sea (SCS). Coherent northward propagation of atmosphere-ocean fields associated with monsoon ISO is seen in all years. To illustrate this in the longitudes of the western BOB, the period May to September 1998 is considered. 10-80 day filtered anomalies of OLR, wind speed and Qnet (net heat flux) all show clear propagation of ISO from 5^0 S to the northern boundary of the Bay of Bengal [32]. This is illustrated in Figure 4. SST anomalies propagate northward in response to northward moving, alternating positive and negative anomalies of Qnet Since the period of the oscillations is about a month in 1998 and 2000 and the northward speed is about 1.40 day^{-1} (1.8 m s^{-1}), the phase of the ISO at the equator is opposite to that in the North Bay of Bengal. It is noted that this anti-correlation was not clear in 1999 because the 10–20 day monsoon ISO is energetic. In the South China Sea, a few episodes of northward propagation of convection and Qnet anomalies are clear to the

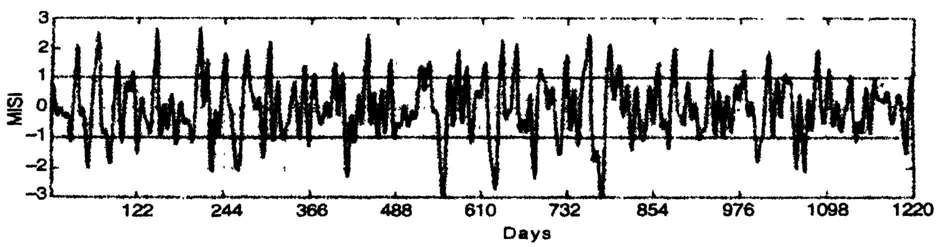

Figure 3. (a) Normalized Monsoon Intra-seasonal Oscillation Index (MISI) [29] for 10 years (each year has 122 days starting from 1954). Thin solid line corresponds to ± 1 normalized unit.

north of 50 N followed by strong northward moving SST anomalies as in the Bay of Bengal.

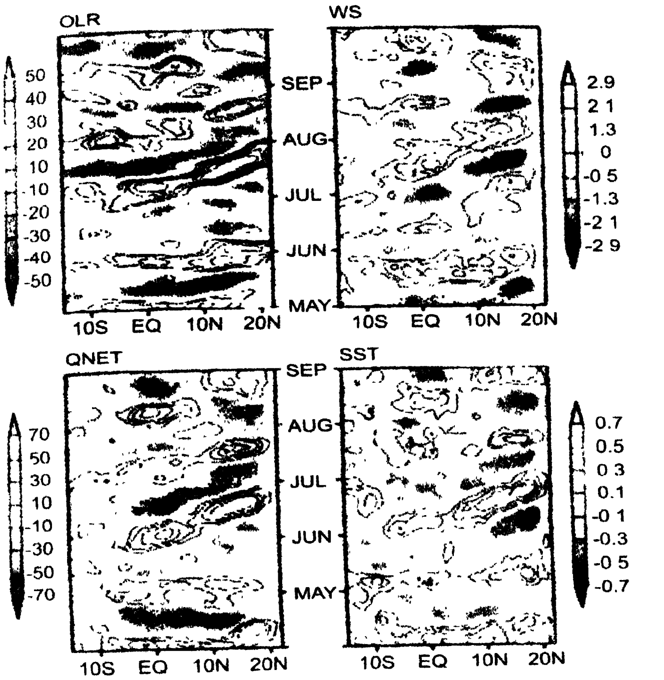

Figure 4. Time latitude sections of 10-80 day filtered anomalies of OLR (W m^{-2}), windspeed (m s^{-1}), Qnet (W m^{-2}) and SST (^{0}C) averaged over 85-90^{0} E in the summer of 1998

The Qnet and SST (Sea Surface Temperature) anomaly fields have large zonal extent, from the Arabian Sea to the South China Sea and beyond, during the active and quiescent phases of the monsoon [16]. Thus, the estimation of Qnet is based on a number of approximations, its variability is in reasonable agreement with that obtained by SR based on BOB buoy data but for one important difference. Buoy data from the northwestern BOB shows that air temperature in the summer monsoon can be higher than SST, particularly in periods when the sky is clear and SST is rising.

2.3 *Inter-annual variability :*

The Indian summer monsoon has vigorous intra-seasonal oscillations in the form of 'active' and weak (or 'break') spells of monsoon rainfall [33]. These active and break spells of the monsoon are associated with fluctuations of the tropical convergence zone (TCZ) [15,34-36]. The intra-seasonal oscillations (ISO's) of the Indian summer monsoon represent a broadband spectrum with periods between 10 and 90 days but have two preferred bands of periods [35,37,38], one between 10 and 20 days and the other between 30 and 60 days. Several modeling studies show that a significant fraction of the inter-annual variability of the seasonal mean Indian summer monsoon is governed by internal chaotic dynamics [39-42]. Mehta and Krishnamurti [43] examined the inter-annual variability of the 30-50 day mode with the winds at 850 and 200-hPa for the period 1980-84 using the European Center for Medium Range Weather Forecasts (ECMWF) operational analysis. Singh and Kripalani [44] and Singh *et al* [23] used long records of daily rainfall data over the Indian continent and examined the 30-50 day oscillation. They, however, could not come to a clear conclusion regarding relationship between the ISOs and the inter-annual variability of the Indian monsoon rainfall. Ahlquist *et al* [45] studied radiosonde observations at 12 Indian stations between 1951 and 1978 and examined ISOs with periods longer than 10 days but did not try to relate the ISOs with the inter-annual variability of the monsoon.

A model proposed by Goswami [6] describes, how the ISOs influence the seasonal mean and inter-annual variability of the Indian monsoon. The model is based on the similarity between the spatial structure of the dominant ISO mode and that of the inter-annual variability. The seasonal summer mean (June-September, JJAS) precipitation distribution has a major zone of large precipitation along the monsoon trough extending to the North Bay of Bengal and a secondary zone of precipitation maximum south of the equator over the warm waters of the Indian Ocean. These two maxima in the seasonal mean precipitation represent two favored locations of the TCZ during the summer monsoon season [15,6].

Active and break monsoon conditions are traditionally defined based on a precipitation criterion [33]. A circulation-based definition of active and break monsoons may be useful for various purposes. During an active phase of the Indian monsoon, typically there is more precipitation over central India and a stronger monsoon trough.

2.4 *Coherent Intra-seasonal oscillations :*

The Global Experiment of 1979 [43] revealed that the ISO involve significant modulation of SST and turbulent fluxes at the air-sea interface in the Bay of Bengal and equatorial west Pacific. Accurate estimation of surface fluxes were made during the winter of 1992-93 [46] by Coupled Ocean Atmosphere Response Experiment (COARE) in the west Pacific. This led to the unambiguous demonstration [47] that the slow oscillation of SST in the COARE region is a response to intra-seasonal fluctuation of surface heat, momentum and buoyancy fluxes associated with the eastward propagating, equatorially confined Madden-Julian oscillations (MJO)[48]. The evolution of atmospheric convection, surface heat fluxes and SST over the Indo-Pacific warm pool associated with MJO has been studied extensively [49-51]. The results of these studies suggest that at least on intra-seasonal time scales, equatorial warm pool SST changes are primarily driven by surface heat flux. The observations from moored surface buoys in the western Bay of Bengal show coherent 20-40 day SST fluctuations during the summer of 1998 with peak to peak range of upto 2^{0} C, which are not captured by the weekly National Centers for Environmental Prediction (NCEP) SST analysis [52]. Large fluctuations in the net surface heat flux Qnet are associated with the monsoon ISO. During the active or convective phase of the ISO, the sky is cloudy and surface winds are strong, leading to negative Qnet while the calm or quiescent phase is marked by clear skies and light winds, giving large positive Qnet. SR shows that the intra-seasonal SST changes can be understood to the first order of approximation as a response to oscillations of Qnet. The root-mean-square differences between TMI (TRMM Microwave Imager) fields and three-day buoy data in this region are about 0.6^0 C for SST and 1.3 m s^{-1} for wind speed [53].

3. Link between stratosphere and monsoon rainfall

The Quasi-Biennial Oscillation (QBO) in the mean zonal wind is the dominant feature of the tropical stratosphere (20-30 km). The easterly and westerly wind regimes alternate regularly with a period varying from about 24 to 30 months. The discovery of the QBO in tropical stratospheric winds stimulated the search for stratospheric-tropospheric links.In the late 1970's some evidence for link between the IMR (Indian Monsoon Rainfall) and stratospheric zonal winds was reported [54-56]. Thapliyal [56] reported that the mean January circulation features at the 50-hPa levels are able to indicate the deficient monsoon rainfall in westerly QBO years. Thapliyal [57] extended this study by examining data of mean monthly global circulation features in the lower stratosphere for the period 1965-80. He found that in winters of the easterly QBO years, a subtropical ridge is situated over the northern hemisphere around 20° N. Such winters are followed by normal monsoon activity. Thus, Thapliyal [56,57] suggested that the January circulation features at 50-hPa levels could indicate the deficient (normal) monsoon rainfall in westerly (easterly) QBO years.

Mukherjee *et al* [58] found a significant (at the 5% level) simultaneous correlation of +0.39 between the monsoon rainfall and mean zonal wind for June-August at 30 hPa level using wind data for Balboa (9° N, 80° W) for the period 1951-82.

An important feature of the QBO is the downward phase propagation. The wind reversal first appears above 30 km and propagates downward at a speed of about 1 km/month. Using this fact, Bhalme *et al* [59] related the January 10-hPa zonal wind anomalies at Balboa with IMR and found a correlation of 0.52 during the period 1958-85. They found that IMR tends to be less (more) than normal during an easterly (westerly) anomaly. The results of Thapliyal [57] and Bhalme *et al* [59] may appear to be contradictory; however, it must be noted that the results are based at different levels (50-hPa and 10-hPa).

At the beginning of 1990's, additional evidence has been found on the links between stratospheric winds and IMR. The India Meteorological Department [60] uses 16 parameters in an operational long range-forecasting model. Two of these parameters are related to the stratosphere, namely the 50-hPa-wind pattern in winter and the 10-hPa zonal wind pattern in January.

Parthasarathy *et al* [61] found a relationship between the tropical zonal stratospheric winds at the above 3 stations and rainfall in 5 homogeneous regions of India. They also found that the standardised wind anomalies averaged separately for the dry and wet rainfall years are characterised by opposite signs at all these 3 stations, thus confirming the strong association between them. Singh [62] found that the stronger are the QBO easterlies at 10-hPa levels in January, the larger is the area over the country, likely to suffer from dry conditions Thus, the QBO seems to play an important role in the interannual fluctuations of IMR.

Further, Kripalani *et al* [63] related the Northern Hemisphere 50-hPa geopotential heights with IMR. They found significant positive correlations along 10°–20° N during January and February. However, the maximum relationship is seen during March, with high positive correlation over the Canadian sector and high negative over the East Asian sector.

Meehl [64] suggested that the coupled interaction between ocean and atmosphere contributes to a mechanism that produces a biennial component of interannual variability in the tropical Indian and Pacific regions. His premise was that a wet (dry) monsoon year would be followed by a dry (wet) monsoon year He showed that the ocean heat content provides the one-year time scale memory necessary for the biennial mechanism Whether this mechanism has any relationship with stratospheric QBO needs a separate investigation.

4. Forecasting of monsoon rainfall

In India, agricultural and industrial economy largely depends upon monsoon and so its forecasting is very important. Meteorological scientists have records of earlier monsoons, cycles of climates, measuring instruments to measure speed of wind, humidity, and temperatures *etc*. But these tools are not sufficient for forecasting of monsoon.

July and August are the major rainy months over Northwestern (NW) parts of India. Investigations by De and Biswas [65] and Pillai and De [66] have shown that end of July/August rainfall is important in deciding the seasonal rainfall of the year. By the end of August we get a clear indication of the performance of monsoon of the year. Frequency of breaks is also maximum in July and August. As such the correct prediction of weekly rainfall in July and August can be a useful input for the long-range prediction also.

In 1977, India and U.S.S.R. jointly carried out research and they found out that the south-west monsoon is depend on so many activities going on in Antractic and Pacific oceans. Dr.Vasant Gowarikar, Dr.Thapaliyal and others [60] worked out a module of 16 parameters to study monsoon. With the study of 16 parameters and available statistics of earlier monsoon, scientists started forecasting of monsoon since 1990 and more or less the forecasting was satisfactory or close to accuracy. In March 2003, meteorologists changed some parameters but main parameters remained same. This study tells us about long-term forecasting, while study of satellite pictures gives information on movement of clouds, cyclones, and measurements of wind, temperatures, humidity give picture of local changes.

Blanford [67] was the first to attempt a forecast of monsoon based on the hypothesis that "varying extent and thickness of the Himalayan snows exercise a great and prolonged influence on the climate conditions and weather of the plains of northwest India". The success of Blanford's tentative forecasts during 1882-85 encouraged the meteorologists to start operational LRF (Long Range Forecasting) of monsoon rainfall covering the whole of India in 1886. Since then the LRF of monsoon has become an important operational task of the IMD (India Meteorological Department). The forecasts after 1895 were based on (i) Himalayan snow cover, October to May, (ii) 'local peculiarities' of pre-monsoon weather in India and (iii) 'local peculiarities' over Indian Ocean and Australia [68].

Sir Gilbert Walker [69-71], the Director General of IMD, has initiated extensive studies of worldwide variation of weather elements such as pressure, temperature, rainfall *etc*., with the aim of developing an objective method for LRF of monsoon rainfall over India by expanding the works of Hildebrandsson [72], Lockyer and Lockyer [73] and others who had drawn attention to the global-scale oscillations in surface pressure. These studies led Walker to identify three large-scale pressure seesaw patterns; two in the Northern Hemisphere (North Atlantic Oscillation (NAO) and North Pacific Oscillation (NPO)) and one in the Southern Hemisphere (Southern Oscillation (SO)). While the NAO and NPO are essentially regional in nature, the SO has since been recognized as a phenomenon with global-scale influences. The SO was later linked to the oceanic phenomenon called El Niño in the east-equatorial Pacific characterized by warming of the sea surface along the Peru coast; this led to the theory of Walker Circulation [74]. Walker also succeeded in removing the subjectivity in the earlier forecast methods by introducing the concept of correlation in the field of LRF of monsoon rainfall. With these pioneering contributions to the field of LRF, Sir Gilbert Walker has been most closely identified with the early attempts at monsoon forecasting in India and his findings are relevant even today.

Walker [75] also attempted LRF for sub-regions of India by dividing the country into 3 homogenous regions namely (i) Northeast India, (ii) Peninsular India and (iii) Northwest India. Regression formulae were developed separately for these three regions, which had been subsequently revised several times [68]. After that very little progress was made in LRF of monsoon rainfall until the early eighties when several studies have re-established the strong link between the monsoon rainfall variability and ENSO (El Nino Southern Oscillation) using better data sets.

Pre-monsoon surface pressure and thermal fields over India

Monsoon being the result of land-sea heating contrast involving large-scale seasonal reversal of pressure, temperature and winds, many studies have been carried out to identify useful predictors based on the pressure and thermal fields during antecedent winter and pre-monsoon seasons. Parthasarathy *et al* [76] developed a predictor parameter, which they called West Central India (WCI) pre-monsoon (March-April-May) pressure, represented by the mean of sea level pressure (SLP) at six stations (Jodhpur, Ahmedabad, Bombay, Indore, Sagar and Akola) located in the core region of high correlation, which showed a CC of –0.63 (significant at 1% level) with the AISMR (All India Summer Monsoon Rainfall) during 1951-80. Earlier, Parthasarathy *et al* [77] found that the mean surface temperatures at these stations during MAM season also showed high correlation (0.6) with monsoon rainfall for the period 1951-80.

Mooley and Paolino [78], using maximum and minimum temperature data for the period 1901-75, revealed that a predictor based on May minimum temperatures over western Indian region has good potential for LRF. Krishna Kumar *et al* [79] identified two predictors based on the minimum temperatures during March over East Peninsular India and during May over west central India.

The operational LRF model [60] of the India Meteorological Department also uses three minimum temperature parameters representing northern, central and east coastal areas of India.

Pre-monsoon 500 - hPa Ridge location over India

Banerjee *et al* [80] identified the mean latitudinal location of the 500-hPa ridges along 75^0 E in April over India. This is considered to be one of the most important predictors. The mid-tropospheric anticyclone over southern India migrates from 11.5^0 N in January to its northernmost position of 28.5^0 N during July. From October, the ridge starts shifting back southward. Mooley *et al* [81] found a CC (Correlation Coefficient) of 0.71 (significant at 0.1% level) between the April ridge location and AISMR during 1939-84; a more northward location indicates better performance of the monsoon and *vice versa*. It is conjectured that the northward and southward displacements of this mid-tropospheric anticyclonic circulation are related to the seasonal march of the solar radiation and the associated diabatic heat source. The anomalies in the seasonal evolution of the mid-tropospheric circulation, as measured by the April ridge location, can be taken to be a good precursor of the slowly varying planetary-scale circulation. A delayed northward displacement of the ridge is considered to indicate large-scale anomalous descending motion over the Indian region [82]. In a detailed diagnostic study using daily locations of the 500 hPa ridge during the pre-monsoon months of March-May for the period 1967-87, Krishna Kumar *et al* [83] found that the ridge location in March showed a CC of −0.47 with AISMR, while in April it showed a CC of +0.63. They also found that the negative correlation of the March ridge was more dominant with the monsoon rainfall of the peninsular India, while the positive correlation of the April ridge was more dominant with the monsoon rainfall of northern India. The difference between the two ridge locations (April minus March) shows a CC of 0.73 with AISMR. Though the 500-hPa ridges has shown consistently significant relation with monsoon rainfall in recent years, the subjectivity involved in the determination of its location imposes some limitation on its reliability.

Upper tropospheric winds over India

Monsoon circulation over India involves marked changes in the upper tropospheric wind field. Keeping this in view, many studies have shown that the upper air winds during their pre-monsoon transition phase can provide a useful predictor. Verma and Kamte [84] and Joseph [85] have identified the association between Indian monsoon rainfall and 200-hPa meridional wind components for the month of May, and indicated its potential for prediction of the seasonal rainfall. Parthasarathy *et al* [86] have further investigated the relationship between meridional wind index (arithmetic average of 200 hPa meridional component of wind for May at Bombay, Delhi, Madras, Nagpur and Srinagar) and AISMR by using an extended data set for the period 1964-88 and found a CC of -0.72 (significant at 0.1% level).

ENSO indicators

Giving the importance to the ENSO phenomenon on the climate variability in the tropics and over several other regions of the globe, many predictors have been developed representing the strengths of both its atmospheric component, the Southern Oscillation (SO), and its oceanic component, the El Niño. Walker [75] developed an index of SO based on a combination of pressure, temperature and rainfall. Subsequent workers have developed several other indices of SO using different combinations of stations mainly based on pressure data [87,88]. The most commonly used Southern Oscillation Index (SOI) as a measure of the strength of the Walker Circulation across the Pacific, is taken as the normalized difference between the SLP (Sea Level Pressure) anomalies at Tahiti and Darwin.

However, the CC's between various SO Indices during preceding winter and spring seasons and AISMR are not sufficiently high for LRF as the relationship develops simultaneously and even follows the monsoon season [89,90]. Shukla and Paolino [91] found that the CC of AISMR with Darwin SLP during winter (Dec-Jan-Feb) was positive while that during spring (March-April-May) was negative. Because of this change of sign in the CCs, the CC of the winter to spring tendency (MAM-DJF) of SLP at Darwin with AISMR during 1901-81 was found to be much higher (-0.46, significant at 0.1% level) than the CCs of individual seasons. Thus, the winter to spring tendency is considered to be a reliable precursor for the nature of SO during the monsoon and later months.

The planetary-scale tropical SLP anomalies associated with the SO occur in conjunction with the episodes of large-scale sea surface temperature (SST) anomalies (El-Niño/La Niña) in the tropical Pacific [82,92,93]. It has generally been observed that warmer SSTs in central and eastern parts of equatorial Pacific are associated with lower monsoon rainfall [94,95]. Parthasarathy and Sontakke [96], using COADS SST data during 1951-80 have identified three important regions in the Pacific Ocean whose SSTs have shown significant relationships with the AISMR. These three regions are: (i) 14°-26°N, 128°-140°E; (ii) 14°-20°N, 176°-160°W and (iii) 14°N-10°S, 148°-100°W, whose MAM-DJF tendencies in SST showed CCs of 0.4, -0.51 and -0.52 respectively with AISMR. The intensities of El Niño events are generally assessed on the basis of the average SSTs over three Nino regions in the Pacific Ocean, widely known as NINO1+2, NINO3 and NINO4. Among these, only NINO4 SST (MAM-DJF) shows statistically significant CC (-0.54 during 1951-80) with AISMR.

Cross-equatorial flow

The observational studies of Saha [97], Pisharoty [98] and Cadet and Reverdin [99] and modeling studies of Washington *et al* [100] and Shukla [101] have established the importance of the role of cross equatorial flow over Indian Ocean and moisture flux from both Indian Ocean and Arabian Sea regions in Indian monsoon rainfall, mainly over the west coast. However, there is some difference of opinion regarding the relative dominance of fluxes from Indian Ocean and Arabian Sea. The East African low-level jet is one of the most important manifestations of the cross-equatorial flow involving large-scale moisture and momentum transport [102]. Cross-equatorial flow develops during the onset phase of the monsoon season and its strength, if predictable, can provide an important predictor for AISMR Hastenrath [103] suggested the use of SST's over the Arabian Sea and Parthasarathy and Sontakke [96] attempted to represent the strength of cross-equatorial flow in the Indian Ocean region by Nouvelle-Agalega SLP difference as well as SST's. However, none of these observations could find practical utility in the development of LRF schemes for AISMR. Thus, in spite of the known physical link of cross-equatorial flow with monsoon rainfall, there has been very little progress in identifying useful predictors based on it. Futher works are needed to find the possible link between cross-equatorial flow and monsoon rainfall.

Northern Hemispheric surface air temperature

Many efforts have been made to link the Northern Hemispheric (NH) mean surface temperature anomaly with the strength of the Indian summer monsoon by using the long period data on hemispheric mean surface temperatures. Verma *et al* [104] identified the NH winter surface air temperature anomaly (January+February) as an important predictor for LRF of AISMR. This parameter showed the CC of 0.56 during 1951-80 maintaining its significance even during the later years, and is recognized as one of the most important predictors.

Eurasian/Himalayan Snow cover

The earlier attempts made by Blanford and Walker brought out the association of greater Himalayan snow cover with deficient monsoon rainfall over India during 1880-1920. Subsequently, the reported snow accumulation showed very large variability and the relationship with the monsoon rainfall was found to be opposite compared to the earlier four decades [82]. Though this led to the dropping of snow cover as a predictor by the IMD in 1950, the recent availability of more reliable satellite estimates of snow cover extent revived interest on this parameter and several studies have shown a statistically significant inverse correlation between the Eurasian/Himalayan winter snow cover and AISMR [105-108]. The spatial extent of Eurasian/Himalayan snow cover during the winter is considered to be an important slowly varying boundary condition for the subsequent development of monsoon circulation and therefore is a potential predictor with strong physical link [109]. Parthasarathy and Yang [110] examined the relationship between Eurasian snow cover (1974-1992) and AISMR and found a CC of -0.47 for the month of February. Satellite data, unfortunately, are not available for long periods and also suffer from several inhomogeneities [111], which need to be clarified to develop a useful predictor representing satellite derived snow cover.

Quasi-Biennial Oscillation

The Quasi-Biennial Oscillation (QBO) in the mean zonal wind of the tropical stratosphere (20-30 km), with easterly and westerly wind regimes alternating regularly with a period varying from 24 to 30 months, has been found to have strong association with the performance of monsoon over India. Mukherjee *et al* [58] found a significant simultaneous CC of +0.39 between the monsoon rainfall and zonal wind (JJA) at 30-hPa using wind data of Balboa (9° N, 80° W) during 1951-1982. Taking cue from the fact that the wind reversal first appears above 30 km and propagates downward at a speed of about 1 km/month, Bhalme *et al* [112] related the January 10 hPa zonal wind anomalies at Balboa with AISMR and found a CC of 0.52 (significant at 1% level) during 1958-85. AISMR tends to be less (more) than normal during easterly (westerly) anomaly. Though very promising, the 10 hPa data from Balboa are not regularly reported after 1988 and efforts are being made by some groups to use 10 hPa wind data from other tropical stations like Ascension Island (8°S, 14°24'W) and Singapore (1°40'N, 104°E) having reasonably long-period data.

Spatial patterns of predictor-rainfall relationships

The spatial distribution of the relationship of any predictor with Indian summer monsoon rainfall can be studied by computing its CC's with the sub-divisional monsoon rainfall. Most of the predictors are known to show the highest CC's over northwestern and central India, and the lowest CC's over northeast and extreme southern parts of the Peninsula. The spatial patterns of CC's of most of the predictors with the sub-divisional rainfall have been found to be strikingly similar to those of AISMR. These patterns are generally consistent with the predominant first EOF (Empirical Orthogonal Functions) mode structure of the monsoon rainfall over India [82] and therefore essentially reflect the spatial coherence of AISMR.

Techniques used in LRF studies

Most of the studies on LRF of Indian monsoon rainfall are based on empirical or statistical techniques. These statistical techniques range from simple correlation analysis to advanced procedures such as canonical correlation analysis and neural networking.

Almost all the predictors identified so far have been based on correlation analysis. Though correlation is a very useful diagnostic tool in bringing out the association between various meteorological fields, it is highly sensitive to the data window over which it is calculated, both in terms of the position and the length of the window in the time domain. This imposes certain limitations on the reliability of the predictors.

The most commonly used statistical technique for LRF of monsoon rainfall is the linear regression analysis. A large number of regression models (simple as well as multiple) have been proposed so far [113]. The predictors for the model are either subjectively chosen representing various important forcings on the monsoon or entered into the scheme by following some objective criteria. Both approaches have their own limitations; the subjective selection may not optimize the variance explained while the objective selection is highly sensitive to the data window and may result in overfitting to the data sample [68,96,114]. As the regression models tend to acquire sample-specific characteristics, their reliability is better assessed by testing on as large an independent data set as possible.

Auto-regressive integrated moving average (ARIMA) models were also used to forecast the AISMR as well as the monsoon rainfall over Northwest-India and Peninsular India, and were reported to have shown marginally better forecast skill over the multiple regression models [115]. However, the auto-correlations in AISMR during the period 1871-1990 are statistically insignificant [116]. In view of this, the applicability of ARIMA models for monsoon rainfall forecasting is doubtful.

Gowariker *et al* [60] developed parametric and multiple power regression (MPR) models with 15 predictors for LRF of AISMR, which were later, modified to include 16 predictor parameters. The parametric model is qualitative and indicates either the monsoon rainfall to be excess or deficient, depending upon the proportion of favourable/unfavorable parameters out of the total of 16 parameters.

Thapliyal [68] has developed dynamic stochastic transfer (DST) models for the prediction of AISMR as well as the monsoon rainfall over peninsular and northwestern India. In this method, the position of 500 hPa sub-tropical ridge over India has been considered as an input for the dynamic transfer component, coupled with a stochastic transfer system represented by an ARIMA process and the monsoon rainfall as the output.

Thapliyal [115] evaluated the relative performance of multiple regression, MPR, ARIMA and DST models and found that the DST model has the highest accuracy among those models. However, this model considers only one predictor as input and it is desirable to develop DST models involving multiple parameters representing various forcings of the monsoon system.

Due to the spatial variability of monsoon rainfall over India, the forecasting of countrywide mean rainfall is of limited practical utility. Keeping this in view, Krishna Kumar [117] attempted LRF of sub-divisional monsoon rainfall by canonical correlation analysis (CCA) technique, using monsoon rainfall data from 29 meteorological sub-divisions in India as the predictand data set and the SST patterns (MAM-DJF) over the Pacific Ocean and minimum temperatures (March and May) over India as predictor data set during the period 1958-87. He found that the spatial extent and the magnitudes of useful skill scores for sub-divisional LRF are much larger than those obtained with multiple regression analysis [118]. Thus, CCA technique appears to be a promising method for LRF of the spatial patterns of monsoon seasonal rainfall.

Compared to the number of studies using empirical methods, the studies on the seasonal prediction of monsoon rainfall using general circulation models (GCMs) are very few. This may be partly because of the lack of skill in the simulation of monsoon rainfall over the Indian subcontinent by most of the GCMs [119]. Also, there are marked differences found in the monsoon precipitation simulated by different GCMs (WCRP, 1992). The fact that the simulation of the summer monsoon rainfall over the Indian region is very sensitive to the initial conditions [120] also create serious problems in this context. Ju and Slingo [121] and Soman and Slingo [122] have demonstrated that the seasonal integrations of GCMs could simulate strong and weak monsoon circulations based on the SST distributions over tropical Pacific and Indian Oceans.

Secular variations in the AISMR-predictor relationships

Most of the predictors showed insignificant CC's with AISMR till 1950 and the CC's became significant only around the year 1951. However, there are some exceptions like Darwin SLP tendency and Pacific SST, which showed significant CC's for relatively shorter periods around 1891 and 1921. The CC's of some predictors have even changed their sign during the early part of this century.

Parthasarathy *et al* [123] have examined the relationship between Bombay SLP and AISMR with an extended data set for the period 1847-1990 and found turning points in the CC's around the years, 1870, 1900 and 1940. They attributed these turning points to delineate between two alternating regimes in the monsoon circulation, identified earlier as 'meridional' and 'zonal' types by Fu and Fletcher [124]. Parthasarathy *et al* [123] concluded that the Indian summer monsoon had passed through two meridional (1871-1900; 1941-90) and two zonal (1847-1870, 1901-1940) circulation regimes during the past 150 years. They also found that the relationship between Bombay SLP and AISMR becomes dominant only when the ENSO variance in Bombay pressure is high and falls apart when the ENSO variance is small.

It appears that during the last 3 or 4 decades, the ENSO phenomenon has played a dominant role in the climate variability in general and monsoon variability in particular. During this period, all the three facets of atmosphere-land-ocean system seem to have been strongly coupled. It is not clear how and why this coupling was not dominant in the earlier decades Annamalai [125] suggests that the presence of decadal-scale oscillations in the predictors themselves may possibly be responsible for the instability in the relationship between AISMR and its predictors. The sliding CC's also suggest that the predictability of the monsoon itself may be having secular variations, which probably is one of the reasons for the temporary 'lull' in LRF research immediately after Walker's time.

5. Instability characteristics of monsoon disturbances

In many cases the onset of Indian Monsoon is sudden and the onset phase is associated with some from of transient disturbances. In most of the cases the disturbances originate in the Arabian Sea and very rarely they originate in the Bay of Bengal. Once the monsoon sets, its further progress takes place due to rain bearing systems like monsoon trough, lows, depressions, mid tropospheric cyclones, *etc*. These synoptic scale systems are considered as perturbations embedded in the basic monsoon current. Many attempts have been made to explain the monsoon disturbances of the Bay of Bengal in terms al dynamic instability. Some scattered studies are available for the systems in the Arabian Sea. The onset phase differs in each year but after the onset a low-pressure area develops in the Arabian Sea, which later develops into cyclonic storm [126]. To investigate the instability disturbances for the formation of the cyclonic storm, we have to first analyse the grid point values of wind and temperature at a particular resolution obtained at standard isobaric levels for a particular period. This is considered as the basic state for the formation of the system.

The system wind has a strong meridional and vertical shear and so longitudinally averaged zonal flow is considered to find its impact in the meridional plane. To get the instability, we have to compute the meridional gradient of absolute vorticity and potential vorticity for verifying the necessary conditions of barotropic, baroclinic and combined barotropic-baroclinic instability for each day. Since the baroclinicity is involved vertical stratification should be taken into account. The required static stability from surface to 100 hPa is computed from the area-averaged temperature using the relation [126]

$$\sigma = -R/P[dT/dP - RT/CpP],$$

where σ is static stability, P is pressure, T is temperature, R is gas constant, and Cp is specific heat at constant pressure. Hence, the static stability is varying only in the vertical direction. Next, computations are carried out to verify the necessary conditions of barotropic, baroclinic and combined barotropic-baroclinic instability in the meridional plane *i.e.*,

$$\beta - Uyy = 0,$$

$$\beta - f_0^2(\sigma^{-1}Up)\,p = 0 \text{ and },$$

$$\beta - Uyy - f_0^2(\sigma^{-1}Up)\,p = 0,$$

where β is Coriolis parameter, U is zonal wind and f_0 is Coriolis force. Here, subscripts p and y implies differentiation with respect to that variable. In this case, β-plane approximation is assumed and so f_0 and β values correspond to 9.25° N, which is the center latitude of the latitudinal belt under consideration. The trajectory of the observed cyclonic storm lies in the North Arabian Sea. So two areas in the longitudinal zone are considered, first from 39° E to 81° E (big area) and second from 51° E to ° E (small area). Thus, all the input parameters and the computations are carried out in the big as well as in the small area. Zonal wind shear increases from big area to small area for the days. Wind shear increases and static stability decreases in the lower levels with time. The necessary condition for barotropic instability [127] is satisfied from lower to upper troposphere. It is true also for the case of necessary condition of combined barotropic-baroclinic instability [126]. The magnitude of meridional gradient of absolute vorticity (β - U_{yy}) as well as potential vorticity q_y (y, p) increases from 31st May to 3rd June. This is illustrated in Figures 5(a) and 5(b).

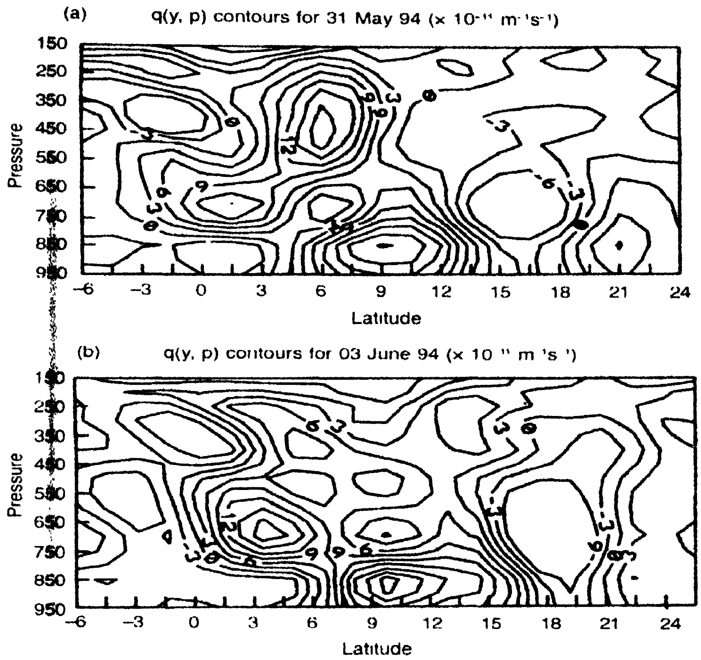

Figure 5. (*a*) and (*b*) Necessary condition for combined barotropic-baroclinic instability [126]

The negative zone is found prominently between 15° N to 20° N. The zero line around 15° N indicates the possible preferred latitude for the formation of the system. Meridional shear is considered to be the primary mechanism for the formation of the system in the whole troposphere.

In the whole troposphere, monsoon disturbance is found to be barotropically unstable. The latitudinal belt of negative meridional gradient of absolute vorticity is reduced but its magnitude is increased with time. This is true for the case of meridional gradient of potential vorticity also.

6. New forecast models for Indian SW monsoon rainfall

The 2002 forecast for the Indian south-west monsoon by the India Meteorological Department prompted severe criticism over the validity of the existing 16- parameter power regression statistical model for Long Range Forecast (LRF). IMD's forecast performance between 1988 and 2002 is presented in Figure 6. As evident from the figure, the character of the monsoon season of July 2002 had been 'unique' and the nature of the anomaly by either hindsight or retrofitting has not yet been pinpointed [128]. As a backlash, the IMD attempted to develop a new set of LRF models. The newly adopted 8- parameter power regression model was first used for the long-range forecasts for the 2003 SW monsoon rainfall. IMD also simultaneously used a 10- parameter power regression and probabilistic models for the long range forecast. A comparative study for the new 8- and 10- parameter

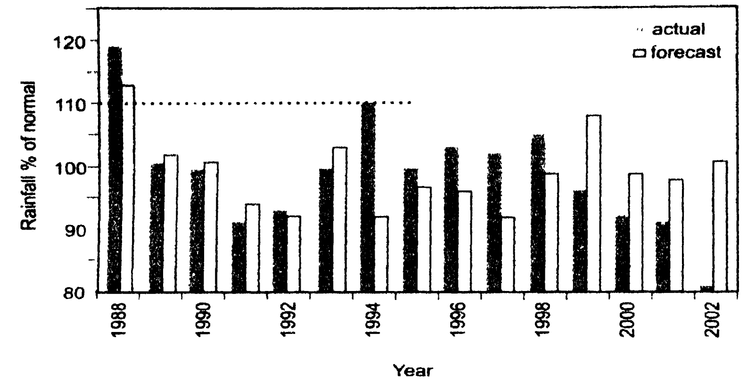

Figure 6. The performance of operational forecasts [128] between 1988 and 2002 (source . IMD, New Delhi)

models as compared to the early 16- parameter model was conducted [128] for 1996-2002, as shown in Table 1.

Table 1. A comparative chart for the 8- and 10- parameter models with 16- parameter model (Source . IMD, New Delhi)

Year	8- parameter	10- parameter	16- parameter
1996	+ 3	+ 3	+ 7
1997	- 1	+ 1	+ 10
1998	- 4	- 2	+ 6
1999	- 5	- 6	- 12
2000	+ 3	+ 3	- 7
2001	+ 1	+ 3	- 7
2002	- 17	- 14	- 20

Note : Actual minus forecast (%)

With these data, it has now become possible to issue the long range forecast in two stages, first in mid- April using data upto March and an update in mid-July using data upto June.

7. Conclusions and scope for future investigations

Different structures of monsoon disturbances are well known over India and neighbouring Seas, but the instability characteristics of such disturbances over Arabian Sea and Bay of Bengal are not very clearly known. Different attempts have been made by the scientists to determine the role of barotropic, baroclinic and combined barotropic-baroclinic instability on the initial formation of such disturbances over Arabian Sea. Further works are required in this line.

The 'strong' monsoon years are clearly associated with higher frequency of occurrence of 'active' conditions and 'weak' monsoon years are clearly associated with higher frequency of occurrence of 'break' conditions. Thus, the frequency of intra-seasonal regimes determines whether it will be a 'strong' or 'weak' Indian summer monsoon. As the seasonal mean monsoon is influenced partly by external forcing and partly by the ISO's, even if the strong (weak) monsoons are not clearly characterized by higher frequency of the 'active' ('break') conditions, the role of ISO's could not be ruled out. The fact that even after separating the contribution of the external forcing, strong (weak) monsoons are clearly characterized by higher frequency of 'active' ('break') conditions indicates that the ISO's play a dominant role in determining the seasonal mean. As the ISO's are intrinsically chaotic, the prediction of inter-annual variations of the Indian summer monsoon becomes difficult and will have to be probabilistic in nature.

The growth of errors in the transitions from active to break is governed by the low frequency 30-60 day oscillations of the monsoon Hadley circulation [129]. The significance of the study is that they are not limited only to the Indian summer monsoon ISO's but represents a fundamental property of tropical intra seasonal variability in general. For example, they are applicable to the eastward propagating Madden-Julian Oscillations [130] in its convectively coupled regime over the Indian Ocean and western Pacific. Though extended range prediction convectively active conditions may remain to be difficult, the conceptual and modeling support can predict dry spells up three weeks in advance.

Navone and Ceccatto [131] have used 'feed-forward' neural network technique for the prediction of Indian monsoon rainfall with two predictors (500 hPa ridge location and Darwin SLP tendency from January to April). They reported that the neural networks could make a better use of the predictive information available in the predictor data. However, further work needs to be done to conclusively establish the superiority of the advanced statistical tool over other methods.

It has been noted that there have been alternating periods extending to 3-4 decades with less and more frequent weak monsoons over India. For example, the 44-year period 1921-64 witnessed just three drought years; during such epochs, the monsoon was found to be less correlated with the ENSO. During the other periods like that of 1965-87, which had as many as 10 drought years out of 23, the monsoon was found to be strongly linked to the ENSO. The problem is an interesting one and to be considered as a future problem. IMD has adopted a two-stage forecast process, the first one on 16 April and the second an update to be made available in mid- July. However, IMD has not got yet the forecasting models peer-reviewed which is definitely in line for ensuring requisite input parameters needed for the statistical models from space satellite data of the Indian Space Research Organisation's (ISRO) satellites such as 'Climatesat', 'Metsat' and 'Oceansat' for further forecasting of the Indian monsoon presently and in future.

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